

Continuous Climb Operations: The following step

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ABSTRACT

Typically air traffic controller manages departure traffic gradually in the airport airspace neighborhoods, providing clearances for the access to higher altitudes determined by conditions of traffic flow mix. This air traffic management implies the realization of several level-offs at each departure which suppose an increase of the fuel consumption firstly and as result the rise of overall cost of operation. Furthermore, not only operational costs are affected but both noise and pollutants emissions are increased, eco-friendly departure procedures requires a special heed because a new international range of requirements desire to abate the environmental impact due to aircraft operations. In order to avoid this inefficient departure procedure, continuous climb operations (CCOs) are defined as novel procedures which will ease the pilot departure perform. CCO is the ideal path an aircraft might fly in the absence of any ATC issues. The aim of this work is to analyze different CCOs techniques and evaluate the feasibility of implement them in a real scenario. A review of diverse CCOs based on different concepts of operation is presented, as minimizing fuel consumption, noise impact, constant climb speed, etc., as well as the definition of the requirements a CCO must fulfill which shape the feasible solution space. Lastly, Palma ATM environment is presented as case study of the viability of implementing CCO procedures among real requirements and expected drawbacks.

Keywords

Trajectory Based Operations, Continuous Climb Operations, Path Optimization.

ACM Classification Keywords

J.2 [Physical Sciences and Engineering]: Aerospace.

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1. INTRODUCTION

Air Transport is one of the largest industries over the world, moving annually million of Euros and providing employment to thousands of people. According to OACI [1], nearly of 3100 million of passengers took the air transport worldwide network in 2013. The number of passengers increased over 5% compared with 2012 and it is expected to reach more than 6400 million to 2030. This increase of demand prompts the necessity to perform a future restructuration of the worldwide airspace [2], by the implementation of novel air procedures which will allow aircrafts to guide themselves over more accuracies trajectories, decreasing the time of flight and likewise helping to reduce the environmental impact.

On the last decade significant research has been performed into climb operations by main stakeholders as NASA, FAA, EUROCONTROL, etc. The CCO aim is to enable aircraft to fly their optimal path within the requirements of the ATM system. IFATCA [3] presented a literature review, up to 2012, and analyzed the requirements a CCO should fulfill if a new procedure might be defined. The potential problems outlined were that these new procedures are more complex and, therefore, will increase operational risk, compliance with the vertical profile would be more difficult to monitor and distinguishing which aircraft is flying a CCO or a level-off route could be difficult.

CCO can be considered as the “little brother” of Continuous Descent Approach (CDA) because, as MITRE [4] concludes in its analysis about potential benefits of the implementation of CDAs and CCOs, with the implementation of these procedures at the USA airports it can be saved around 380 USD million, 90% of them by CDAs and 10% by CCOs. Moreover, the potential benefits can also lead a reduction of 850 metrics tone of CO_2 and 216 tons of SO_x . The reason of CCOs only could save over 10% is, based on [2], because departure procedures are generally fairly efficient.

Nowadays several researches are focused into minimizing the environmental footprint of flight operations. One of the Europe environmental research targets for 2020 is to eliminate CO_2 emissions by 50%, NO_x by 80% and decrease noise by 50% of the 2000 average levels [5]. Torres and Chaptal [6] addresses the optimization of commercial aircraft departure procedures in order to minimize their environmental footprint, defined by noise nuisance near airports, local air quality and global warming, formulating a multi-objective non-linear problem. In the same optimal problem context, Prats et al.[7] and Visser [8] developed

different optimal techniques to tackle the noise abatement in the departure phase. Both researches took into account the fuel consumption as a key indicator although the main key factor is the noise generated by the aircraft and the exposition time of the aircraft in the neighborhoods.

Multi-objective optimization about eco-friendly concepts is always based on the same structure, it is developed a complete path optimization between two points, considering noise, pollutants and fuel consumption as key factors [9, 10, 11]. Although multi-objective optimization theoretically bears in mind all the criteria, later on it is required to transform all except one criterion into boundary conditions of the optimal problem.

This work is organized as follow. A study of CCO structure constitution is presented as well as the most common concepts of operation used in. To assure the integration of a CCO in an airspace environment is necessary to introduce the diverse requirements an aircraft must fulfill inside a controlled block of airspace. Finally, the definition of an example in a real TMA scenario, Palma de Mallorca (Spain), is presented to illustrate some benefits that a CCO can accomplish.

2. CONTINUOUS CLIMB OPERATION

In this section the procedures an aircraft must follow in a CCO are defined and what are the requirements that must be imposed along it. The aim is to establish limits to the aircraft path throughout the departure and not to determine what is the optimal trajectory regarding operational concepts as fuel consumption, maximum thrust, pollutants, etc., ATC requirements and airspace design restrictions. Defining a CCO profile is conditioned to the vertical profile due to lateral positioning is restricted by each public airport procedure

2.1 Concept of operation

A CCO can be defined as the trajectory performed by an aircraft from the runway up to cruise level fulfilling with a concept of operation, in this way, the path can be formulated as:

$$\begin{aligned} & \text{Opt } f(x, y, z, t) \\ & \text{subject to } R(x, y, z, t) \end{aligned}$$

Being:

- $f(x, y, z, t) \equiv$ 4D trajectory.
- $R(x, y, z, t) \equiv$ path restrictions.

Different concepts of operation can be employed to define a CCO. The main characteristic to fulfill is that the climb must be done gradually, without stops up to cruise level, Nonetheless, the way to do the CCO is not unique:

Table 1. Diverse concepts of operation for a CCO.

Concept of operation	Principal Variable
Minimum pollutant emissions	Min Fuel burn $= \text{Min}(\text{Fuel flow} \times \text{time})$
Minimum drag	Based on a 3DoF: $\text{Min } D = \text{Min } T$
Minimum noise footprint	$\text{Min Noise} = \text{Min } f(T)$
Minimum fuel consumption	$\text{Min Fuel Flow} = \text{Min } f(T)$

Constant speed	$V_{TAS} = \text{cnt}; \dot{h} = \text{cnt}$
Constant climb angle	$\gamma = \frac{\dot{h}}{V_{TAS}} = \text{cnt}$

2.2 Climb structure

Currently, the performance of a departure is determined by a flight level roof or by catching particular control-points in a delimited time defined by ATC. In order to build a CCO vertical profile the followings segments must be distinguished:

Table 2. Flight departure phases with its main operational features.

Height limits (ft.)	Aircraft configuration	Operational Concept
Up to 1.500	Take-off (flaps extended)	T_{max}
1.500-10.000	Cruise	$V = \text{cnt} \leq V_{max}$ ATC restrictions
10.000 – H_p	Cruise	$V_a = \text{cnt}$ or $\text{acceleration} = \text{cnt}$ ATM restrictions
H_p – Cruise level	Cruise	$M_a = \text{cnt}$

Being H_p the cross-over altitude, V_{ac} characteristic aircraft speed for climb and M_a characteristic Mach number for climb. Although aircraft can choose its operational concept in the departure, the most typical way is to fly with constant speed until each roof stage and accelerate to the next speed. [12], regarding that aircraft are not operating in an incomprehensible scenario so density changes with altitude and therefore speed increases. Besides this climb structure is the most widespread it is not the only one, Torres and Chaptal [6] release the departure procedure optimization since 35 ft AGL considering flaps retraction operation.

2.3 Airspace Requirements

Every departure has its own operational restrictions which characterize its vertical profile, but most of them can be encompassed inside three types:

1. Flow crossings: supposing the prohibition of going on with the departure, making a level-off, or obstructing an airspace block for an amount of time.
2. Obstacles: buildings, mountains, etc., can restrict the climb profile defining a minimum climb slope.
3. Safety: air traffic controllers have to ease its departure and landing flows mixing.

For each stage there are some typical requirements that all aircraft must fulfill.

2.3.1 Stage 1: Up to 1.500 ft.

This is the take-off phase featured by maximum thrust T_{max} and flaps extended and the aim is to clean the configuration as fast as possible. All the performance limits are strongly restricted by manufacturers, so it is not considered as part of a CCO.

2.3.2 Stage 2: 1.500-10.000 ft

Aircraft operate with a clean configuration, in this phase, a typical ATC constraint is to limit maximum speed to 250kts, although it

can be modified according to each TMA. Likewise obstacles are important here which define a minimum climb slope.

For instance: Maintain 6000 ft except ATC clearance and 6.6% minimum climb gradient to 4000 ft.

2.3.3 Stage 3 and 4: 10.000 – Cruise level

Aircraft should operate without speed limitations, choosing its preference climb speed depending of the ATM scenario. Same restrictions as previous phase can be adopted.

For instance: IAS max 300 kt until 13.000 ft and maintain FL 245 until VOR/DME 112.60.

At the cross-over altitude aircraft fly with M_a up to cruise level and no speed or climb gradient are applied. Typically, the climb gradient is the same as in the cruise level ($\dot{h} = 1.000 - 2000 \frac{ft}{min}$) depending on en-route traffic controllers.

2.3.4 Operational requirements

In addition to airspace requirements there are performances which forbidden to perform a particular vertical profile. The main restrictions are due to thrust capacity because the power plant is responsible to provide enough power for the operation. The climb must be wrapped inside the maximum thrust T_{max} and below the minimum T_{min} which is determined by the stall speed $v < v_{stall}$.

2.3.5 Environmental requirements

Three environmental criteria are the most important:

- **Fuel consumption:** normally fuel consumption is a function of the required thrust to fulfill operational requirements either it is considered a variable which must be minimized. In both cases some restrictions can be formulated in order to block fuel flow:

$$Fuel\ flow\ (kg/s) \leq R_{fuel\ Flow}(kg/s)$$

Moreover, analyzing the influence of the fuel condition in the flight, it can be concluded that it directly affects the available thrust $R_{fuel\ Flow} \rightarrow T_{max}(v_{dada}, h_{dada})$

- **Pollutant emission:** The main problem of considering pollutants is that they cannot be directly evaluated during the operation. The usual way to deal with emissions is to consider them as percentage of consumed fuel, i.e., an emission factor. In this model, CO, HC, NOx and SOx are defined in a Landing/Take-off (LTO) cycle, which includes all activities near to the airport which take places up to 3.000 ft. The calculus is merely a fuel conversion for each pollutant:

$$Emission\ (g) = Fuel\ Burn\ (kg) \times Emission\ Factor\ (g/kg\ fuel\ burn)$$

$$Fuel\ burn\ (kg) = Fuel\ flow\ (kg/s) \times time\ (s)$$

- **Noise:** Noise abatement is usually based also in LTO cycles in which aircraft have to make necessary operations to reduce noise generated in the ground. Generally lateral maneuvers are forbidden so the only manner to abate noise is to act into the thrust, executing cut-backs up to an ATC determined level where the noise footprint is allowed.

$$R_{noise}(65\ dB) \rightarrow T(65\ dB)$$

3. CASE STUDY: PALMA

3.1 Scenario description

The Palma Control Center (ACC) manages, by delegation of Barcelona ACC, the airspace spanned between Palma and Valencia ATC, in the Balearic Islands, and the airspace controlled by “Dirección Regional Balear” is in turn Palma TMA. These functionalities are complemented by Palma, Menorca and Ibiza airport control towers.

Vertical limits of Palma airspace are from the sea level up to FL 245 being the higher usable flight level FL 240. Above this, higher airspace manager is Barcelona. Palma scenario has been chosen because all of its SIDs that are addressed to VOR/DME 112.60 (Menorca) (red circle in Figure 1) have as TMA restriction: *not to fly higher than FL 245*. Moreover, every SID of Palma has two requirements in the stage 2 (example):

- Maintain 6.000 ft. except ATC clearance.
- 6.6% minimum climb gradient to 4000 ft.

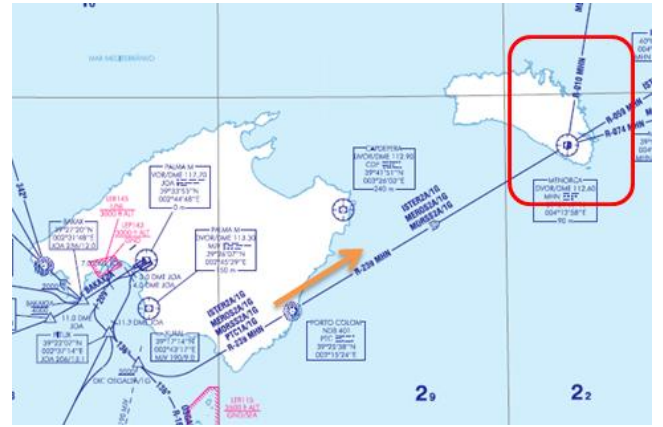


Figure 1. Palma airport SIDs scenario.

This restriction is addressed to ease Palma and Barcelona ATC work, because if aircraft were free to fly directly might generate potential conflicts among en-route and climbing aircraft increasing significantly ATC workload. In Figure 2 it is depicted (ADS-B data) vertical and speed profile of a B727-800 TUI2715 flying from Palma to Stuttgart throughout MEROS2A1G SID (orange arrow in Figure 1).

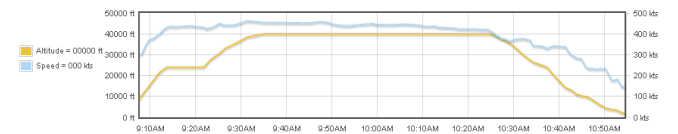


Figure 2. TUI2715 path profile flying from Palma to Stuttgart throughout MEROS2A1G SID.

In figure 2 it is clear to see the level-off aircraft must to do because this operational requirement. This level-off suppose a considerable increase of operational costs and environmental burden so they should be erased.

3.2 Integration of CCOs in Palma.

The aim of implementing a CCO is that every aircraft performs its climb according to a concept of operation which enables to optimize trajectory. Mainly, minimizing fuel consumption is the

most used although currently noise abatement and pollutant emission are gaining supporters.

In order to “freeze” an aircraft throughout its climb in Palma two types of requirements have been attached previously:

1. Aircraft which do not fly to Menorca only have requirements of flow crossing between 1.500 -10.000 ft, therefore, the integration of CCOs can be achieved with the correct manage of air traffic flows.
2. Aircraft which fly to VOR/DME 112.60 have another restriction that prevents to reach cruise level if not have been passed this VOR. The implementation of a CCO has to be restricted up to this point in order to avoid the potential level-off (red line Figure 3).

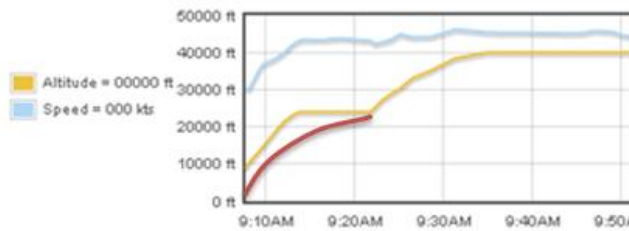


Figure 3. CCO integration up to FL 245.

On the other hand, the implementation of CCOs supposes drawbacks for the air traffic management:

- Major uncertainty due to each aircraft has a different optimal climb profile.
- Need to increase distance between following aircrafts to ensure that at any moment minimum safety requirements are violated.
- Need to increase time windows into potential conflict points among departure and landing flows.
- Lastly, an operational capacity reduction which could inhibit the integration of CCO with step-traffic.

4. CONCLUSIONS AND FURTHER WORKS

After detecting Palma TMA requirements for departure flow and disadvantages due to the integration of CCO on this, it can be concluded that CCO procedures can be implemented in Palma SIDs. Only one SID has particular features that limit the path optimization up to a flight roof. The main requirements which have to be considered in order to integrate a CCO are flow crossings, the existence of obstacles and safety regulations. On the other hand, the principal drawbacks are the increase of operational uncertainty, minimum distance and enlargement on time windows that affect overall operational capacity, which can inhibit the mix

of CCO with normal step-traffic. The concept of operational election adds more uncertainty although it generates benefits for the sought operation as noise, fuel, emissions or operational costs decrease. The analysis of the capacity impact by the integration of mix-traffics will be presented in future works.

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